DUNE PHASE II NEAR DETECTOR

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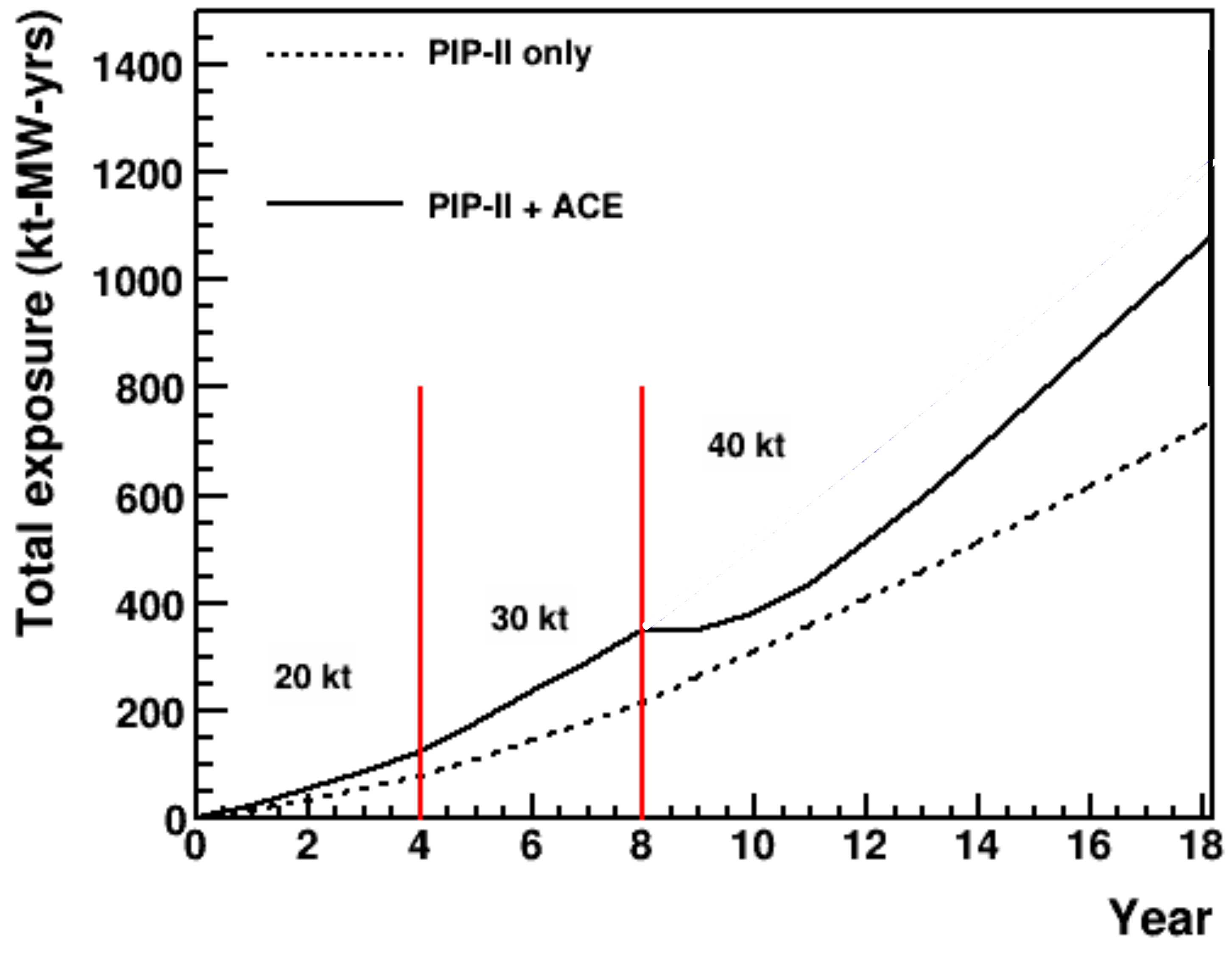
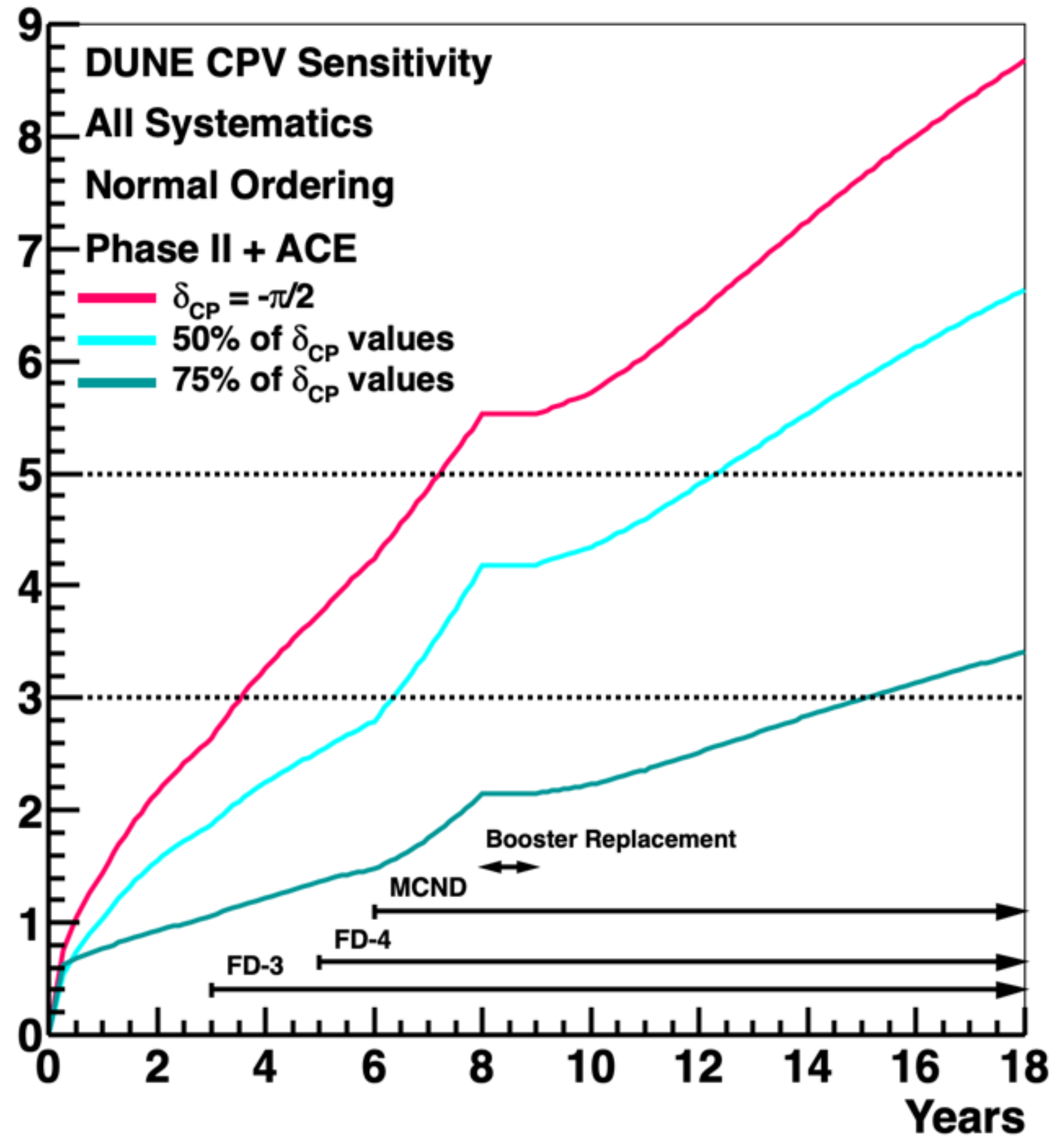
RECAP: EXPOSURE

- A combination of:
  - Accelerator Complex Evolution (ACE): See A. Valishev's talk
  - Additional Far Detector (FD) modules (FD3 + FD4) See M. Bishai's talk
  - Running time

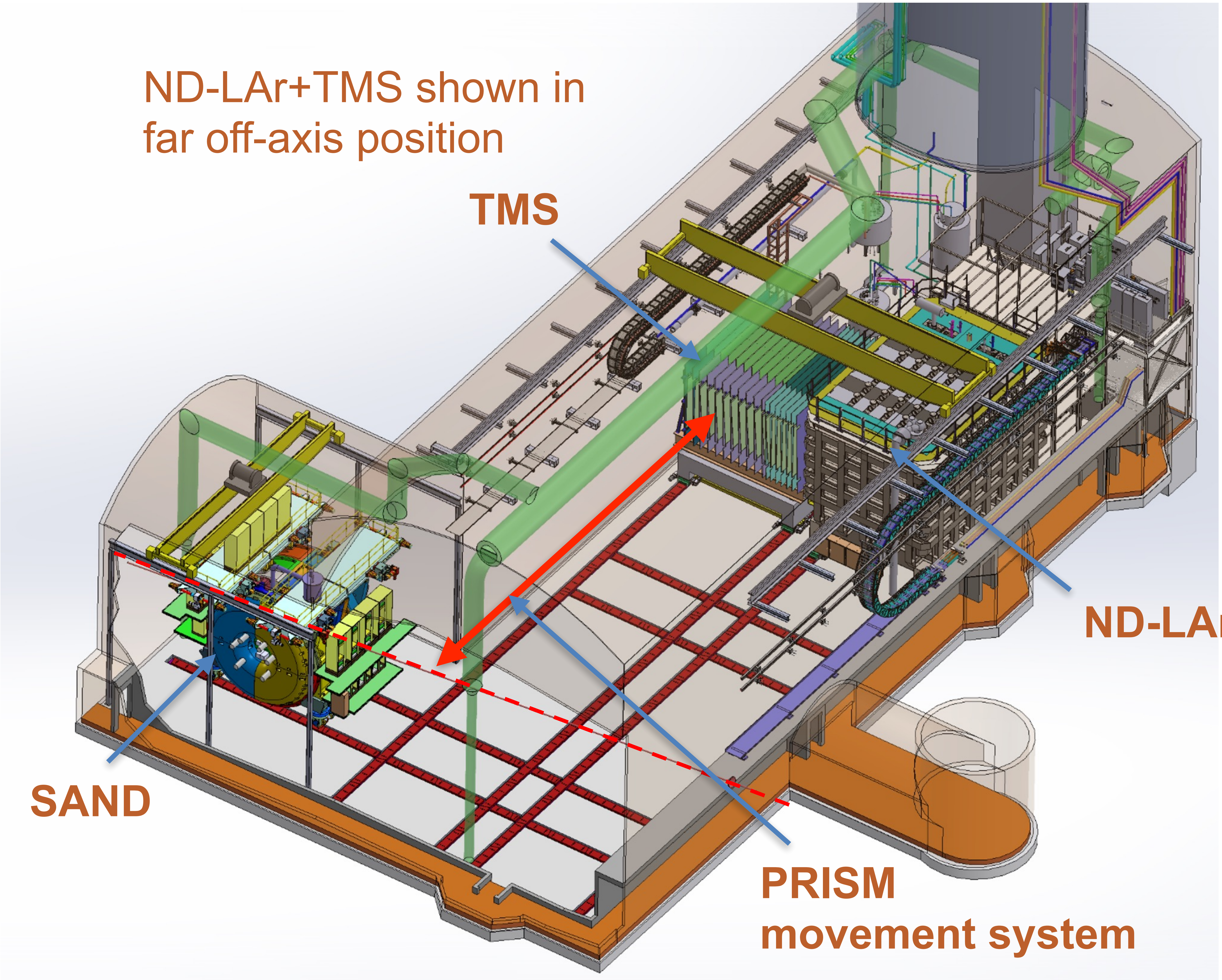
  result in a large increase in FD exposure
- A commensurate strategy for reducing systematics uncertainties is needed.

See C. Marshall's talk





RECAP: PHASE I NEAR DETECTOR

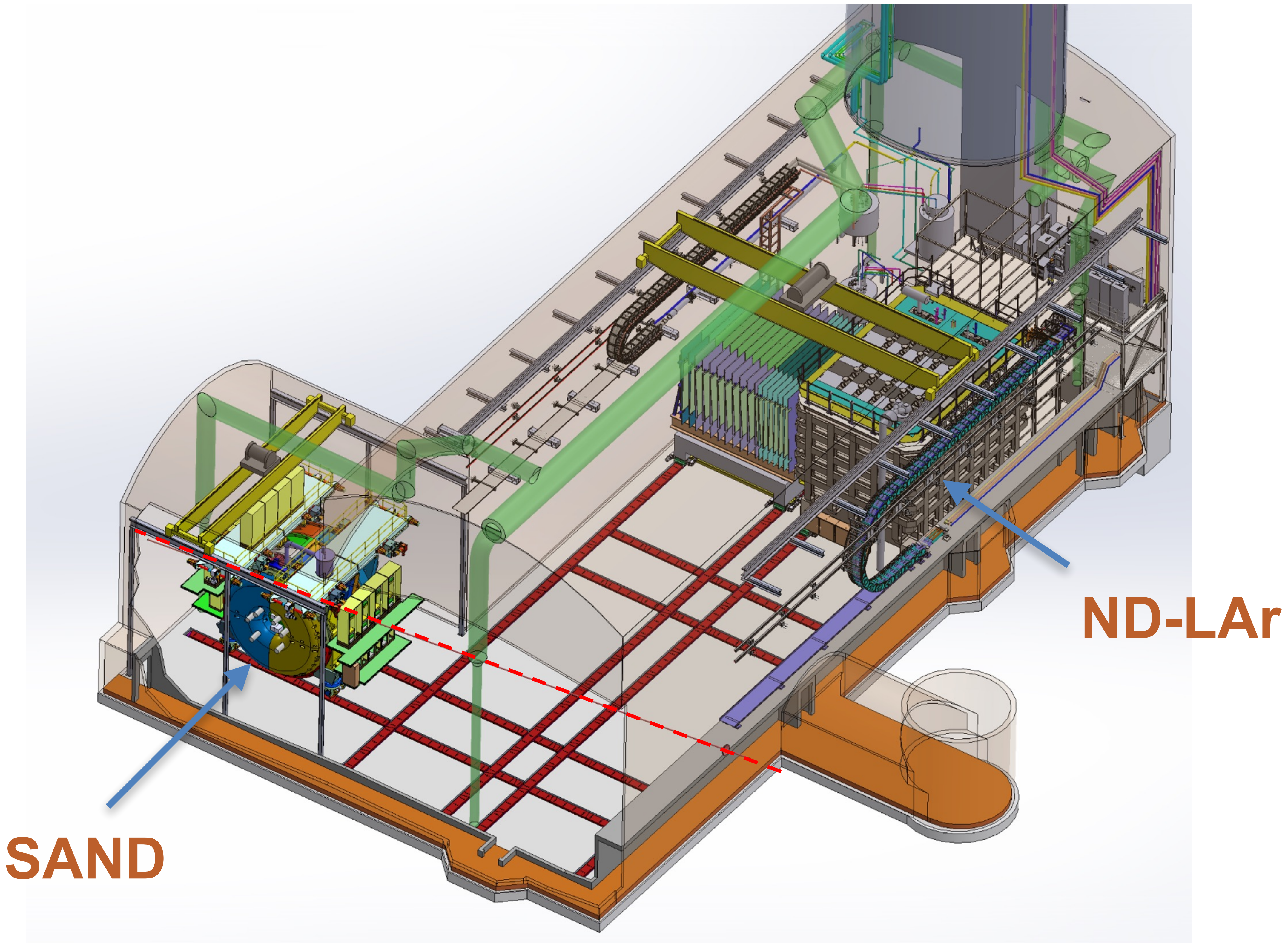


- **ND-LAr + TMS with PRISM movement**
  - **ND-LAr:** 7 x 5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
  - **TMS:** Magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
  - **DUNE-PRISM: ND-LAr** + **TMS** move up to 28.5 m off-axis
- **SAND:**
  - On-axis magnetized neutrino detector with LAr target (GRAIN), tracking (STT), and calorimeter (ECAL)

See S. Zeller's talk

PHASE I ND MEASUREMENT REQUIREMENTS

	Measurement Requirement	Primary Detector
ND-M1	Classify interactions and measure outgoing particles in a LArTPC with performance comparable to or exceeding the FD	ND-LAr+TMS
ND-M2	*Measure outgoing particles in ν-Ar interactions with uniform acceptance, lower thresholds than a LArTPC, and with minimal 2ndary interactions*	*ND-GAr*
ND-M3	Measure the neutrino flux using neutrino electron scattering	ND-LAr
ND-M4	Measure the neutrino flux spectrum using the "low-ν" method	ND-LAr+TMS
ND-M5	Measure the wrong-sign component	ND-LAr+TMS
ND-M6	Measure the intrinsic beam ν_e component	ND-LAr
ND-M7	Take measurements with off-axis flux with spectra spanning region of interest	ND-LAr+TMS + DUNE-PRISM
ND-M8	Monitor the rate of neutrino interactions on-axis	SAND
ND-M9	Monitor the beam spectrum and interaction distribution on-axis	SAND
ND-M10	Assess External Backgrounds	(ALL)



- Phase I ND carries out a measurement program to achieve the systematic errors needed for DUNE Phase I goals using
  - LArTPC system moveable off-axis
  - On-axis (fixed) neutrino detector system

PHYSICS IMPACT: LONG-BASELINE PHYSICS

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- Significant uncertainty in modeling of final state of $\nu-$Ar interactions
  - Modeling dependence needs to be resolved by detailed measurements of the $\nu-$Ar final state
    - Due to limitations discussed later, LAr-based detectors have limited ability to tune/verify this modeling
    - **Does not impact Phase I physics goals, e.g. mass ordering, maximal CP violation scenario.**

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- For more ambitious goals with larger exposure (~few hundred kt-MW-years), these systematics start become important
  - e.g., sensitivity to CP violation induced by a large range of δ_{CP}, ultimate precision on δ_{CP}
- This motivates a detector that
  - Performs full and detailed reconstruction of $\nu-$Ar interactions to verify the modeling
  - **Complements ND-LAr's role in directly connecting to Far Detector observables.**

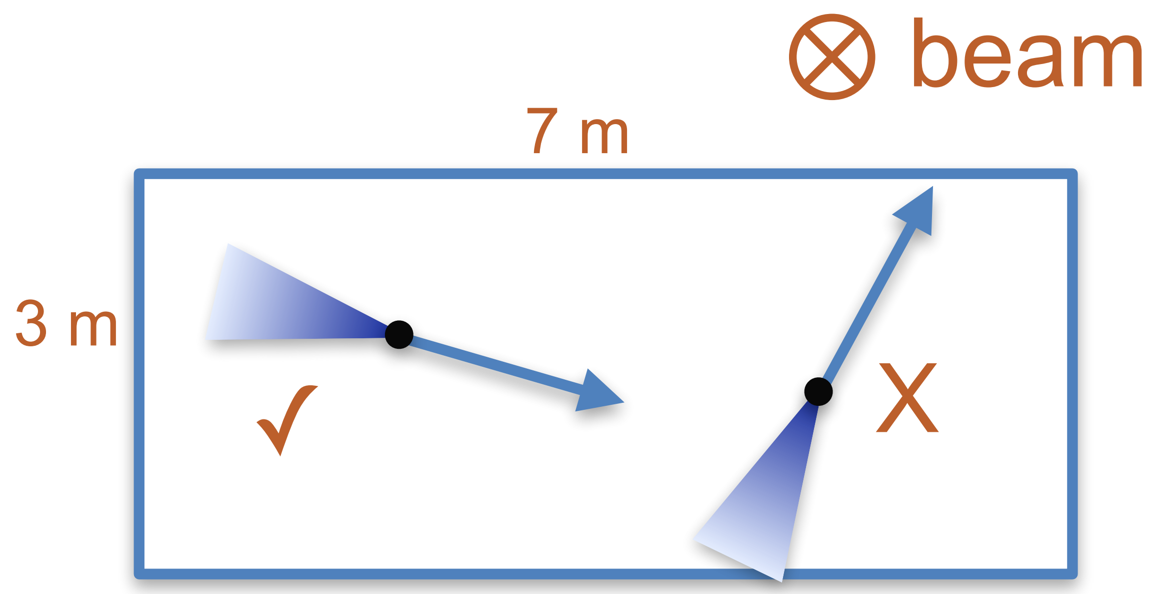
CONSIDERATIONS FOR PHASE II

LAr:

Density: ~1.4 g/cm^3

dE/dx (MIP): ~3 MeV/cm

L_{INT}^{π}: ~70 cm



CONSIDERATIONS FOR PHASE II

- Intrinsic features of LAr-based neutrino detection:
  - Tracking thresholds: 1 cm range in LAr corresponds to ~30 MeV KE for protons
  - Secondary interactions: pions/nucleons interact and produce secondary particles
  - Sign selection: limited ability to distinguish $\pi^{\pm}$ by, e.g. $\pi \to \mu \to e$ tagging
  - Scaleability: Powerful tracking calorimetry capabilities on kton scale.

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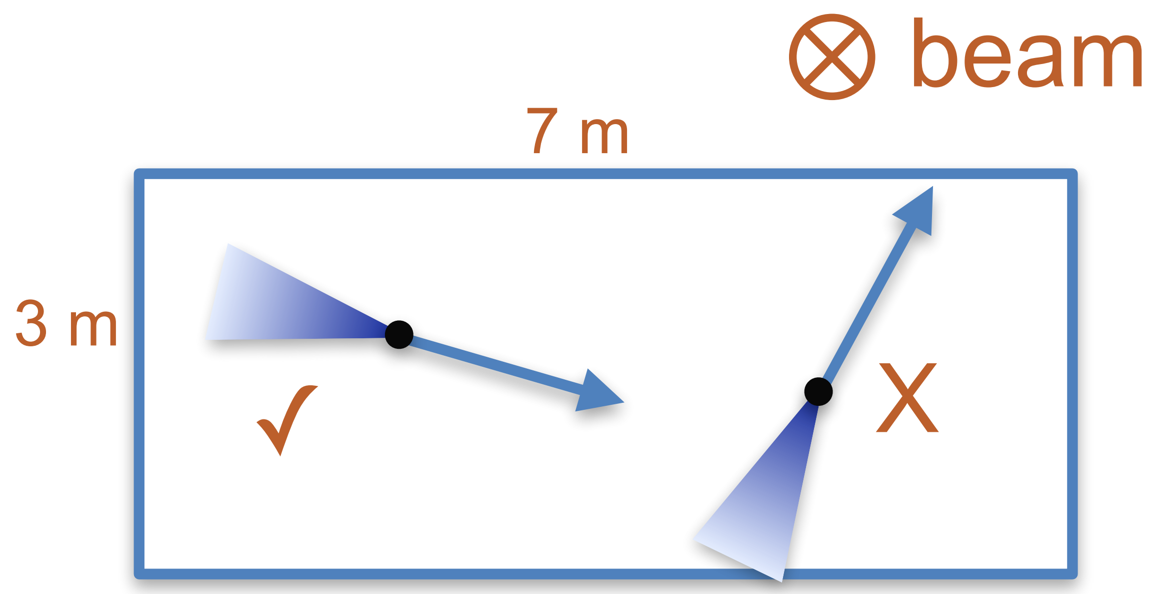

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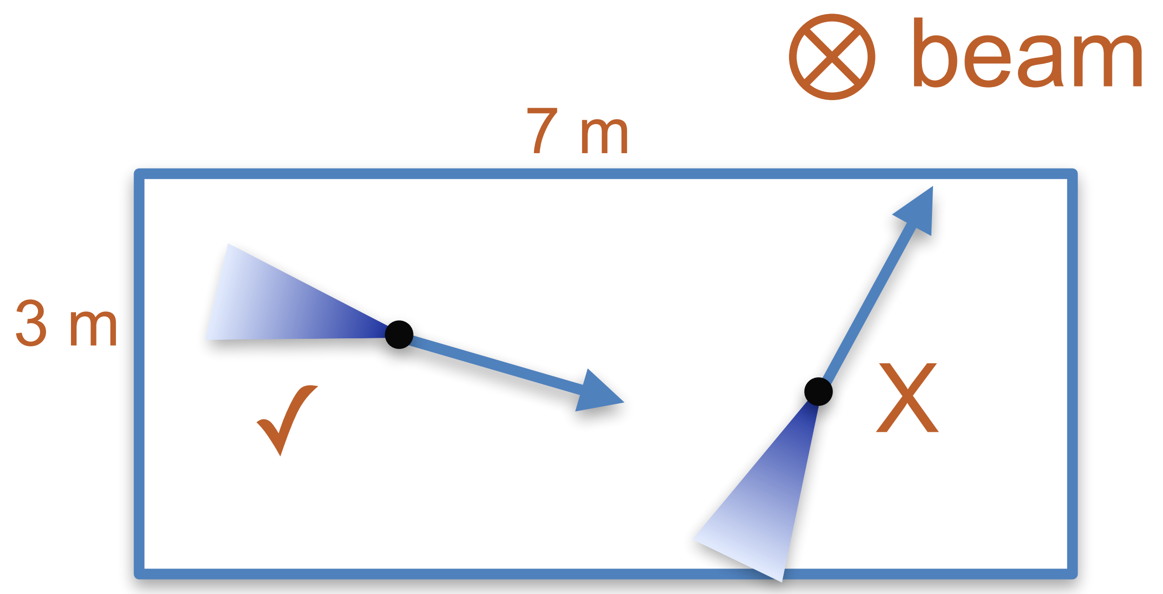

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- Limitations specific to the ND-LAr+TMS design
  - Tracking calorimetry reconstruction requires containment of particles
    - Activity from neutrino interactions span O(m)
  - Size limitations from hall →non-uniform acceptance
    - Acceptance corrections needed to extrapolate to ~uniform acceptance of far detector

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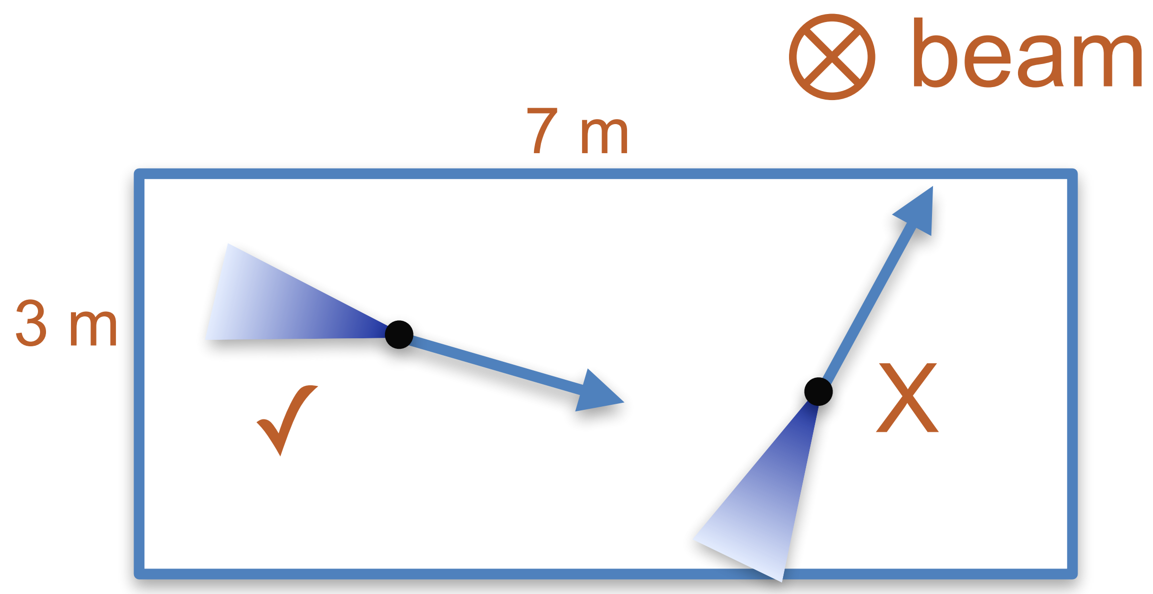

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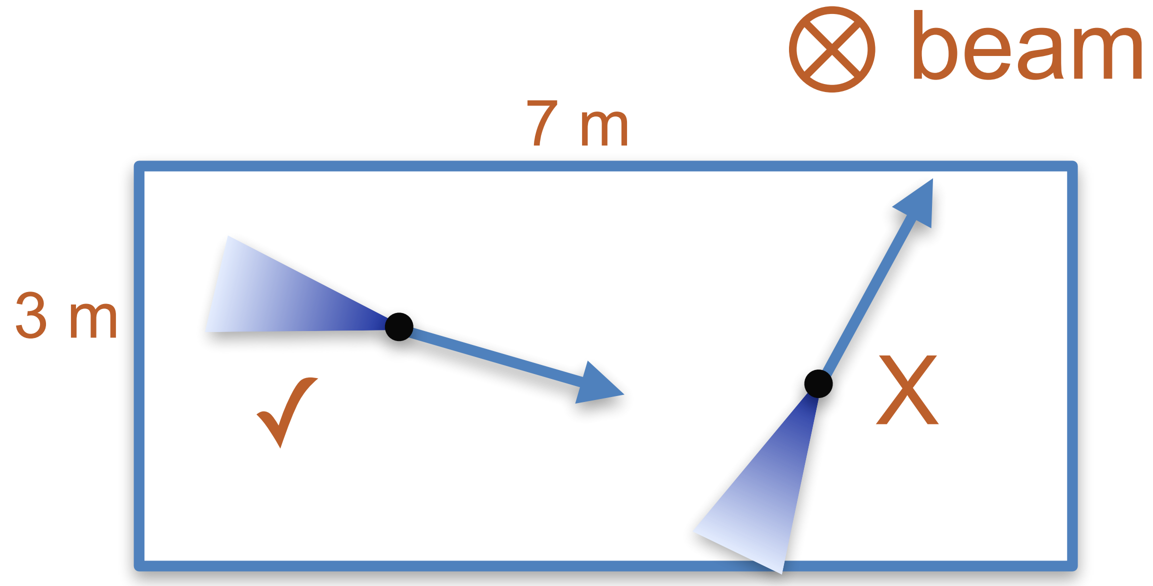

- Motivates a "More Capable Near Detector" (MCND) to overcome limitations of the Phase I ND
  - ***An ND component that is functionally identical to the FD (e.g. LArTPC) remains essential regardless***

MOTIVATION/REQUIREMENTS

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10 B GAr:

Density: ~0.016 g/cm^3
dE/dx (MIP): ~0.025 MeV/cm
L^{π}_{INT}: ~6 x10^4 cm

Interactions/year at 1.2 MW for 1 ton (~60 m^3) of Ar

1.6M ν_μ charged current

30K ν_e charged current

MOTIVATION/REQUIREMENTS

- This motivates a neutrino detector that is:
  - An argon-based tracker
    - match far detector, avoid A extrapolation
  - Low density → gaseous, sufficient Ar target mass → High pressure
    - Lower tracking thresholds: 1 cm range corresponds to 2 MeV KE proton
    - Minimal secondary interactions: interaction lengths > 10 m
  - Magnetized → magnetic spectrometry
    - Momentum estimation by curvature → 4π acceptance
    - Sign selection

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  - Muon detection systems

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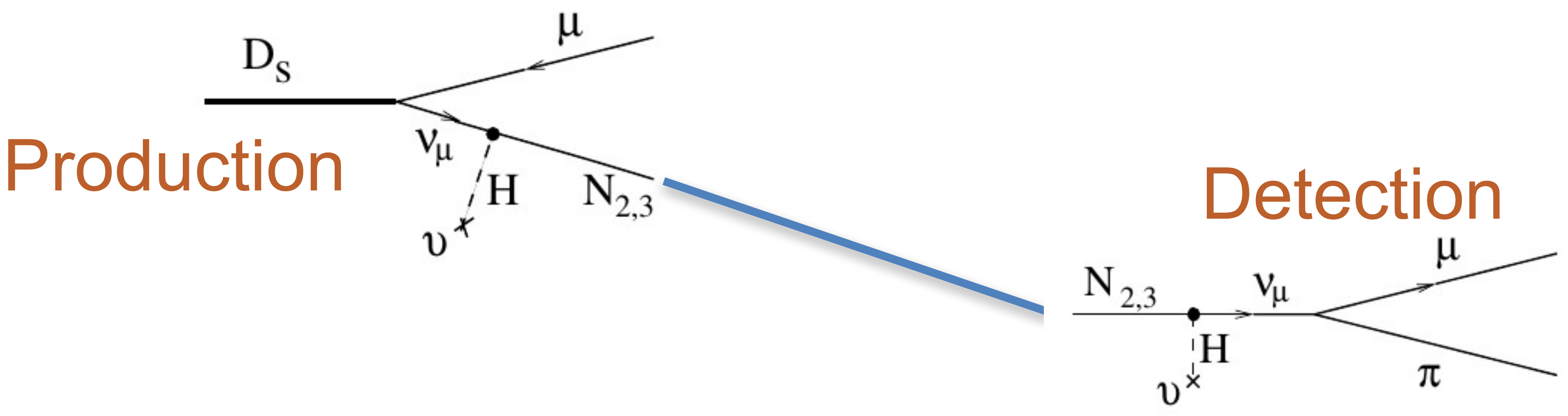
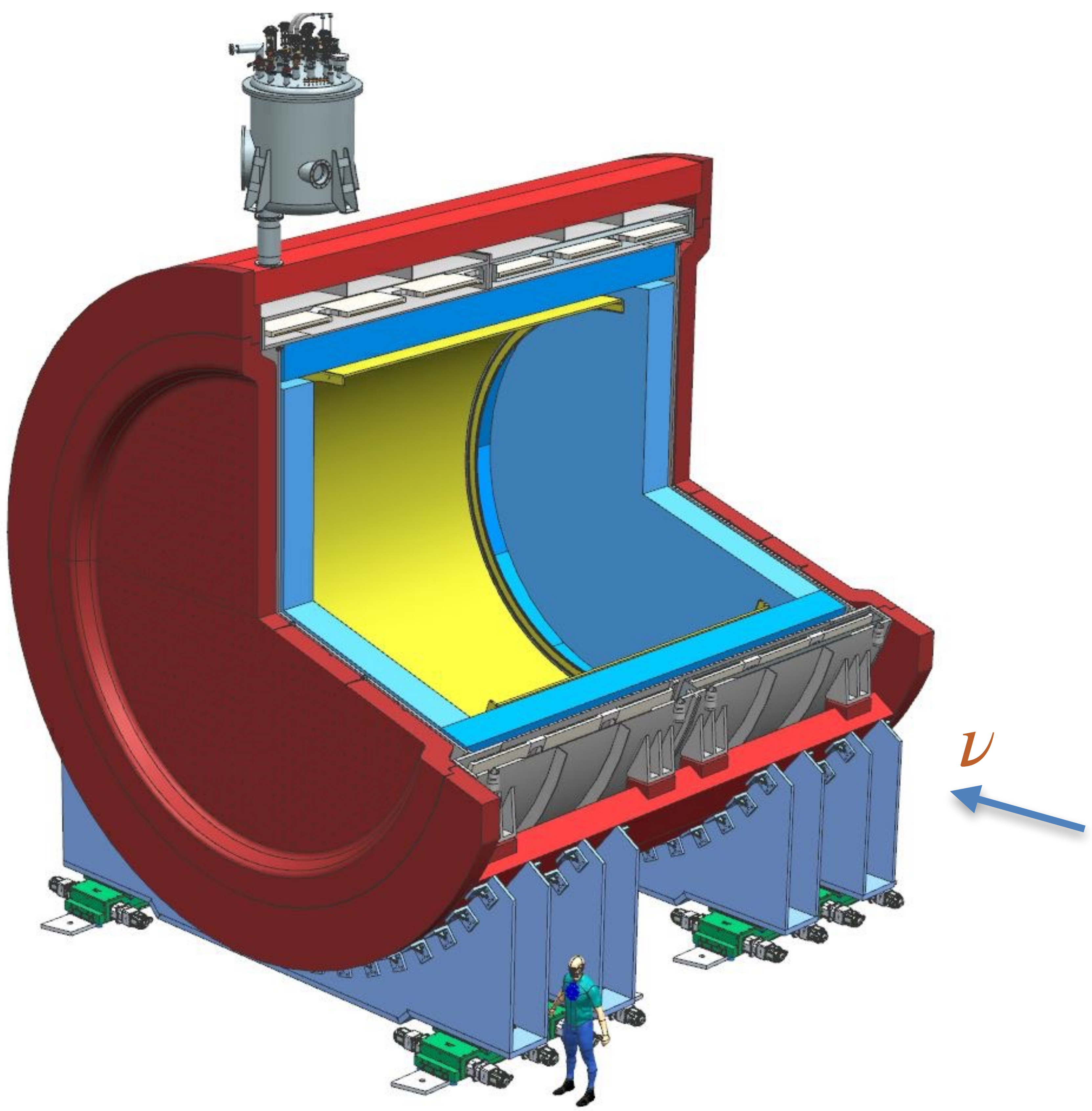
Such a detector would allow full characterization of the final state of ν-Ar interactions

BEYOND THE STANDARD MODEL

- A detector with these capabilities is a powerful probe for BSM physics
  - Particularly for neutral particles (e.g neutral heavy leptons and axions)
    - produced in the beamline
    - decaying in the detector
  - Favorable signal/background for low density tracker:
    - Signals scale with volume
    - Background from neutrino interactions scale with mass
  - Reconstruction:
    - Clean kinematic reconstruction of decay products
    - Neutrino background rejection from recoil particles



ND-GAR:

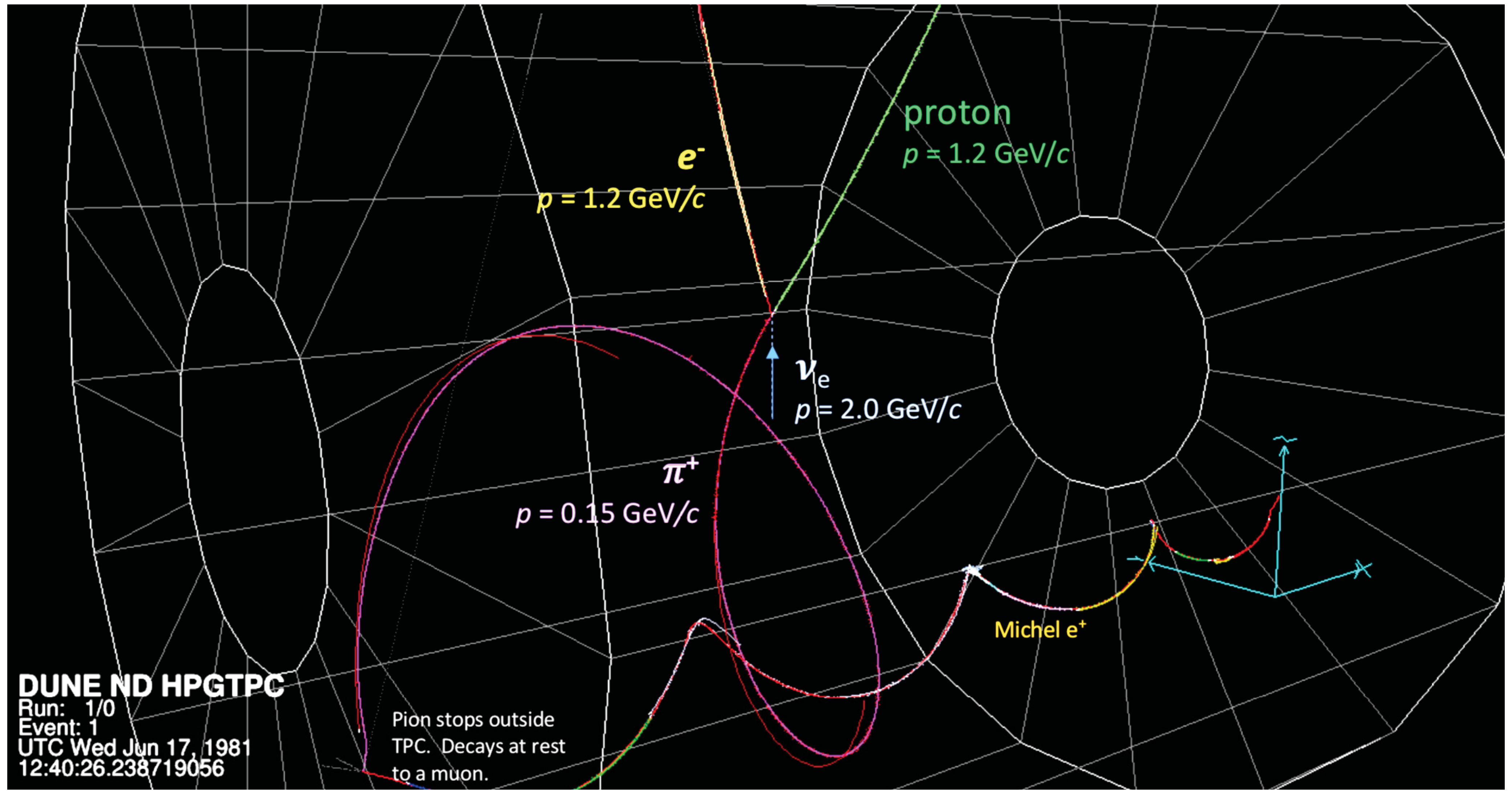


In the Phased approach, the Phase I TMS is replaced by the Phase II MCND

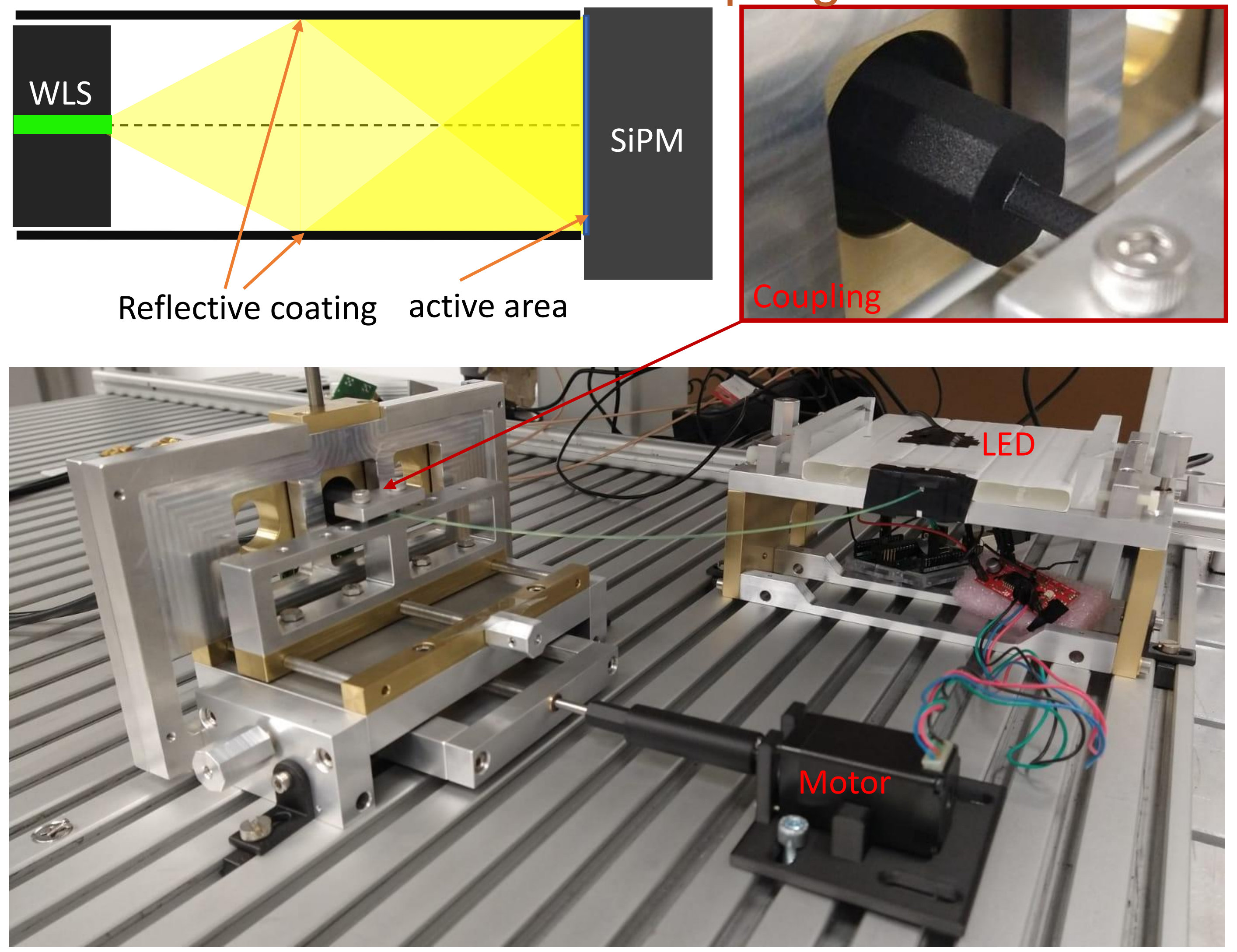
https://inspirehep.net/literature/1854065

- Described in the DUNE Near Detector CDR
  - 0.5 Tesla superconducting solenoid with “partial yolk"
  - 10 bar high pressure argon gas TPC (HPgTPC)
    - 5 m diameter x 5 m length, O(1 ton) of argon target
    - Refurbished ALICE readout chambers
  - CALICE-inspired tile calorimetry system
  - Instrumented magnet yolk for muon detection
- Interest from:
  - Germany (ECAL), India (magnet yolk, vessel), Italy (magnet coils), Spain (light detection, calibration, gas), UK (readout electronics, data acquisition), USA (readout chambers, ECAL)
- ND-GAr would also serves as the muon spectrometer for ND-LAr
  - Placed down-stream of ND-LAr to intercept exiting muons
  - ND-GAr would replace TMS in this role and will move via PRISM

ND-GAR: DESIGN/DEVELOPMENT

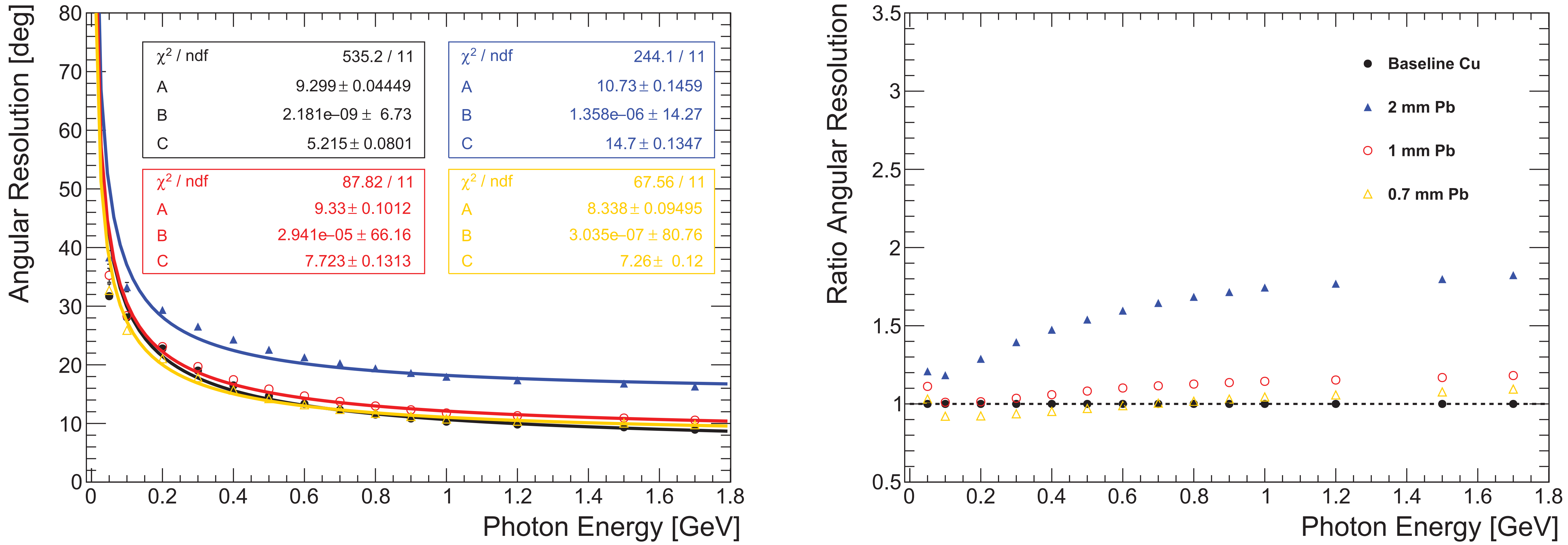


ECAL
Fiber/SiPM coupling



TOAD (Test of Overpressure Argon Detector)
Beam test of readout chambers

- Simulation and reconstruction studies
- Detector optimization
- Prototyping and test beam
- Snowmass white paper (https://arxiv.org/pdf/2203.06281.pdf)
  - "A Gaseous Argon-Based Near Detector to Enhance the Physics Capabilities of DUNE



ECAL radiator optimization

MOVING FORWRD

- A new DUNE Phase II organization was launched in 2023:
  - Coordinator: S. Soldner-Rembold (Manchester)
  - Deputy Coordinator: M. Sorel (IFIC, Valencia)
- The Phase II organization will:
  - Convene working groups to explore options for Phase II detectors (ND and FD) according to physics needs
    - For ND, this includes:
      - New Phase II systems such as ND-GAr
      - Potential upgrades to the Phase I detectors
  - Consolidate and prioritize R&D needs
- A Phase II Near Detector workshop is being planned for this summer.
  - 20-22 June in London, UK

SUMMARY:

- ACE, additional modules, running time greatly accelerate the exposure in DUNE FDs
  - A commensurate strategy for ND measurements to reduce systematic uncertainties is needed to support the physics goals of this exposure such as sensitivity to CP violation arising from a large range of δ_{CP}
- Intrinsic features of LAr-based detectors motivate a detector that:
  - Has low density argon as a target to reduce tracking thresholds and secondary interactions
  - Is magnetized and enveloped by calorimetry + muon detector to provide 4π acceptance
- Such a detector would:
  - allow full characterization of $\nu-$Ar interactions to reduce modeling uncertainties
  - Complement ND-LAr in targeting systematic uncertainties
  - An exquisite instrument to search for a wide class of BSM particle production within the LBNF beam line
- ND-GAr, a detector based on these principles, is described in the DUNE ND CDR
  - There is significant international interest and activity in this detector concept
  - Activities will be coordinated by the new DUNE Phase II organization.